Progress Towards Long-Pulse, High-Performance Advanced Tokamak Plasmas on the DIII–D Tokamak

by

M.R. Wade*

*Oak Ridge National Laboratory

Presented at the American Physical Society Division of Plasma Physics Meeting Quebec City, Canada

October 23–27, 2000

DIII–D NATIONAL FUSION FACILITY

274–00/MRW/rs

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THE GOAL OF THE DIII–D ADVANCED TOKAMAK PROGRAM IS TO DEVELOP THE BASIS FOR A STEADY-STATE, HIGH PERFORMANCE TOKAMAK

- Simultaneously require:
  - High fusion power density $\Rightarrow$ High plasma pressure (high $\beta$)
  - High fusion gain $\Rightarrow$ Good energy confinement (high $\tau_E$)
  - Non-inductive current sustainment $\Rightarrow$ High bootstrap fraction (high $\beta_P$)

- Gain and bootstrap current have conflicting scaling

  - Fusion gain: $\beta \tau_E \propto (\beta N / q) (H_{89} / q^\alpha)$
  - Bootstrap current: $f_{BS} \propto \beta_p \propto q \beta_N$

$\Rightarrow$ Self-consistent scenarios require $\beta_N$ and $H_{89}$ above conventional tokamak values

Definitions: $\beta_N = \beta / (l/aB)$  $H_{89} = \tau_E / \tau_{E, \text{ITER89P}}$
COMPARISON OF CONVENTIONAL AND ADVANCED TOKAMAK FEATURES

Features of Monotonic $q$ Profile:
- High gain
- Moderate turbulence
- Resistive modes limit $\beta$
- $f_{BS} < 30\%$; $H_{89P} < 2.0$; $\beta_N < 2.5$

Pulsed

Features of High $q_{\text{min}}$ and Low Shear:
- High $f_{BS}$
- Reduced turbulence
- Ideal modes limit $\beta$
- $f_{BS} > 50\%$; $H_{89P} > 2.5$; $\beta_N > 3.5$

Potential for Steady-State
HIGH NORMALIZED PERFORMANCE (~10) SUSTAINED FOR 5 $\tau_E$

$\beta \leq 4.7\%$

$\beta N_{H89}$

$q_{min}$

$q(0)$

$f_{bs} \sim 0.5$

$n = 1$ Mirnov Ampl. (G)

$n = 1$ Saddle Loop (G) $\times 10$

$I_p$ (MA) $\times 10$

$P_{NB}$ (MW)

$\langle n_e \rangle$
POTENTIAL FOR STEADY-STATE OPERATION IS ACHIEVED FOR MODERATE REDUCTION IN FUSION GAIN

\[
\begin{align*}
\beta_p & = 0.0 \\
\beta_p & = 0.5 \\
\beta_p & = 1.0 \\
\beta_p & = 1.5
\end{align*}
\]

Fusion Gain

\[
\begin{align*}
q & = 3.1, \beta_N = 2.7, H_{89} = 1.9 \\
q & = 5.5, \beta_N = 3.8, H_{89} = 2.7
\end{align*}
\]

Bootstrap Current Fraction

DIII-D Advanced Tokamak Target
ENERGY TRANSPORT IS NOT SUBSTANTIALLY ALTERED BY THE CHANGE IN $q$ PROFILE

- Neoclassical and empirical scalings predict $\chi \propto q^2$
IMPROVED CONFINEMENT IS CONSISTENT WITH DRIFT-WAVE SIMULATION WITH ExB SHEAR

- GLF23 model* contains ITG, TEM, and ETG with effects of E×B shear
- Self-consistent simulation shows reduction but not suppression of turbulence, consistent with measured $\chi_i > \chi_i, \text{neo}$

Politzer GP1.114
MAXIMUM $\beta$ IS LIMITED BY RESISTIVE WALL MODES

Limiting modes have the characteristics of resistive wall modes:

- Onset is at or above the no-wall ideal limit ($\beta_N \geq 4\ell_i$)
- Growth rate consistent with characteristic wall time
- Real frequency (<100 Hz) consistent with wall time, not fluid rotation
- Proof of principle experiments on feedback control of the resistive wall mode indicate the possibility of raising the $\beta$ limit

See M. Okabayashi Gl1.5
Garofalo M01.004
TEARING MODE BEHAVIOR AGREES WITH NEOCLASSICAL TEARING MODE MODEL

\[ \frac{d\beta_p}{dt} = 0 \]

Perturbations Grow

\[ \frac{dw}{dt} > 0 \]

Perturbations Decay

\[ \frac{dw}{dt} < 0 \]

\( f(T_i) \)

\( f(J) \)
TEARING INSTABILITY MAY OCCUR DUE TO LACK OF CURRENT SUSTAINMENT AND DENSITY CONTROL
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Plasma Shaping $(\beta_N > 3.0)$
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ECCD (Current Profile Control)

Plasma Shaping ($\beta_N > 3.0$)
DEVELOPMENT OF CONTROL TOOLS IS NECESSARY TO EXPLOIT THE PHYSICS OF ADVANCED TOKAMAKS

Plasma Shaping ($\beta_N > 3.0$)

Divertor Pumping (Density Control)

ECCD (Current Profile Control)
DEVELOPMENT OF CONTROL TOOLS IS NECESSARY TO EXPLOIT THE PHYSICS OF ADVANCED TOKAMAKS

Divertor Pumping (Density Control)

ECCD (Current Profile Control)

RWM Feedback Control Coils ($\beta_N > \beta_{N_{no-wall}}$)

Sensor loops

Correction Coils

Plasma Shaping ($\beta_N > 3.0$)
CURRENT PROFILE EVOLVES THROUGHOUT THE HIGH PERFORMANCE PHASE AT CONSTANT PRESSURE
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\[ J_{OH} \propto E_{\parallel} \]

Off-axis ECCD Required
CURRENT PROFILE EVOLVES THROUGHOUT THE HIGH PERFORMANCE PHASE AT CONSTANT PRESSURE

\[ J_{OH} \propto E_{||} \]

Off-axis ECCD Required
CURRENT PROFILE EVOLVES THROUGHOUT
THE HIGH PERFORMANCE PHASE AT CONSTANT PRESSURE

$J_{OH} \propto E_{\parallel}$

Off-axis ECCD Required

$\Rightarrow$ Density control is required
DENSITY CONTROL WILL MAXIMIZE
THE EFFECTIVENESS OF OFF-AXIS ECCD

\[ I_{EC} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)} \Rightarrow I_{EC} \propto \frac{1}{n^2} \text{ at constant } \beta \]

Simulation (99411.1800)
\( P_{EC} = 2.3 \text{ MW} \)
\( I_p = 1.2 \text{ MA} \)

Achieved Density
DENSITY CONTROL WILL MAXIMIZE THE EFFECTIVENESS OF OFF-AXIS ECCD

\[ I_{EC} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)} \Rightarrow I_{EC} \propto \frac{1}{n^2} \text{ at constant } \beta \]

Simulation (99411.1800)
\[ P_{EC} = 2.3 \text{ MW} \]
\[ I_p = 1.2 \text{ MA} \]

- New Inboard Cryopump
- Private Flux Baffle Reduces Recycling
- New Contoured Tiles With Reduced Gap and Height Variation

- New divertor allows pumping in high triangularity shape

Watkins GP1.138
DENSITY AND IMPURITY CONTROL HAS BEEN DEMONSTRATED IN LONG-PULSE ELMING H-MODE DISCHARGES WITH $\beta_N H_{89P} \sim 7.5$ FOR OVER 25 $\tau_E$

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**Graphs:**
- $I_P \times 10^6$
- $P_{INJ} (W)$
- Density ($cm^{-3}$)
- $\beta_N \times H_{L89}$
- Wall Rate (Torr-$\ell$/s)
- Wall Inventory (Torr-$\ell$)
- $f_z (\rho = 0.2\%)$
- $f_z (\rho = 0.7\%)$

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West GP1.121

274-00/rs
INTERNAL MAGNETIC MEASUREMENTS INDICATE THAT THE CURRENT PROFILE IS NOT EVOLVING
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RWM $\beta$ LIMIT HAS A SIGNIFICANT DEPENDENCE ON PLASMA SHAPE

Data windowed to $0.75 < \ell_i < 0.85$, $\beta_N > 4 \ell_i$

\[ S \equiv (I/aB) q_{95} \]

Maximum $\beta_N$

- Experimental scans at constant $I/aB$

$S = 5.2$ \hspace{1cm} $S = 6.7$

$\kappa = 1.8; \; \delta = 0.6$

$\kappa = 2.0; \; \delta = 0.9$
RWM $\beta$ LIMIT HAS A SIGNIFICANT DEPENDENCE ON PLASMA SHAPE

Data windowed to $0.75 < \ell_i < 0.85$, $\beta_N > 4 \ell_i$

- Experimental scans at constant $I/aB$
- Stability calculations at constant $q$
SUMMARY

- Substantial progress has been made in the development of long-pulse advanced tokamak scenarios
  - $\beta_N H_{89} \sim 10$ for $5 \tau_E$
  - $\beta_N H_{89} \sim 9$ for $16 \tau_E$

- Stability
  - Resistive wall modes are the $\beta$ limiting instability in most discharges with $q_{\text{min}} \geq 1.5$
  - Neoclassical tearing modes limit $\beta$ in discharges with $q_{\text{min}} \sim 1$ and sometimes limit the duration of higher $q_{\text{min}}$ discharges

- Confinement
  - Local heat diffusivity on high $q_{\text{min}}$ plasmas similar to that found on conventional sawtoothing H–mode plasmas
  - Electron and ion temperature profiles are well simulated by an ITG model including $E \times B$ shear

- Current evolution
  - Non-inductive current fraction is 60%–75% in high $q_{\text{min}}$ discharges
  - Remaining inductive current is peaked off-axis

- Control tools
  - Density and $\beta$ control demonstrated by operating at $\beta_N H_{89} \sim 7$ for 6.3 s with $\beta$ at >90% of the 2/1 tearing mode limit
EXTENSION OF HIGH PERFORMANCE RESULTS RELY ON MITIGATION OF RESISTIVE MHD MODES (RWMs and NTMs)

High Bootstrap Fraction Discharges

- $\beta_N$ limited by resistive wall modes (RWMs)
  $\implies$ Need feedback stabilization

- Duration limited by current evolution
  $\implies$ Need off-axis ECCD

Long-Pulse, High-Performance Discharges

- $\beta_N$ limited by neoclassical tearing modes
  $\implies$ Need NTM stabilization